



From slopes to streams: Geospatial characterization of landslide dynamics and downstream impacts in the Western Ghats highland panchayats, Kerala, India

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Abstract

The windward slopes of the Western Ghats in Kerala are increasingly experiencing frequent and catastrophic landslides, driven by intense monsoonal rainfall, complex topography, and rising human pressures. Highland Local Self Government (LSG) regions such as Mariyapuram and Vathikudy in the Idukki district, and the upper catchment area of the Manimala River, have emerged as critical areas of concern due to recurrent landslides. This study evaluates landslide susceptibility and downstream impacts in the Mariyapuram–Vathikudy Local Self Governments (LSGs) and the upper Manimala River Basin. The analysis integrates geospatial analysis with governance-focused disaster risk reduction (DRR) strategies. The methodology used includes applying frequency-ratio algorithms to generate Landslide Susceptibility Index (LSI) maps, followed by risk classification and validation using historical landslide data. Landslide susceptibility maps, generated using frequency-ratio analysis, categorize the 112.26 km² Mariyapuram–Vathikudy region into high (17.52%), moderate (65.78%), and low (16.69%) susceptibility zones. In comparison, the 189.68 km² upper Manimala catchment comprises high (25.37%), moderate (70.45%), and low (4.18%) susceptibility zones. This study identifies potential downstream impact zones that, although not located directly on steep slopes, remain considerably vulnerable to secondary hazards such as debris flows and sedimentation. The outcomes are designed to support LSG-level disaster risk reduction (DRR) initiatives and micro-level planning and mitigation strategies. This research underscores the importance of a localised, landscape-sensitive approach to managing landslide risks that accounts for both primary hazard zones and their wider impact areas.

Keywords: Landslide, frequency ratio, downstream impact, local self-governments, disaster risk reduction, Western Ghats

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1 Introduction

The Western Ghats, renowned globally for their abundant biodiversity and designated as a UNESCO World Heritage site, are increasingly susceptible to landslides, particularly during the intense rainfall associated with the south-west monsoon. The region's steep slopes, weathered surface of rock formations, extensive soil layers, and heavy precipitation contribute to its significant vulnerability to landslides (Kuriakose et al., 2009b; Sajinkumar et al., 2011; Prasannakumar and Vijith, 2012; Yunus et al., 2021; Achu et al., 2024; Yunus et al., 2025). In recent years, numerous

landslides have severely impacted the area under Local Self Governments (LSG) situated on the windward slopes, resulting in loss of life, displacement of communities, destruction of infrastructure, and enduring social and economic challenges (Kuriakose et al., 2009a; Sajinkumar et al., 2011; Pradeep et al., 2023; Yunus et al., 2025). The vulnerability to landslides in the Western Ghats can be generally categorized into intrinsic and downstream components. Intrinsic vulnerability refers to a landscape's natural susceptibility, determined by characteristics such as slope steepness, geological composition, soil thickness, land use, and drainage patterns. Conversely, downstream vulnerability refers to

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the cascading effects of landslides on lower-lying areas and river systems, where debris flows, channel blockages, and flash flooding can exacerbate risks (Sarkar and Kanungo, 2004). These vulnerabilities exhibit spatial variability and necessitate customized, site-specific mitigation approaches. Given the localized and recurring nature of landslide hazards, Local Self Governments (LSGs) play a crucial role in disaster risk reduction and enhancing community resilience. By engaging communities, adhering to land use regulations, promoting environmentally sustainable development, and utilizing hazard maps in local planning, Local Self Governments (LSGs) can mitigate both local and downstream landslide risks (UNDP, 2004; UNDRR 2019; KILA, 2020, KSDMA, 2020; NDMA, 2025).

Enhancing local governance and institutional preparedness are essential to fostering sustainable, disaster-resilient development in the Western Ghats' landslide-prone regions. Despite increasing efforts to map landslide-prone regions in the Western Ghats, many studies still lack the large-scale data necessary for effective local-level planning. Assessments of landslides at the regional level often do not adequately capture the intricate variations in slope stability, land use, and socio-economic conditions within specific Local Self Governments (LSGs), thus limiting their utility for local planning and targeted risk mitigation. (De Graff et al., 2012; Milevski et al., 2024). Additionally, these studies seldom consider the dynamics of downstream vulnerability, where landslide debris and sediment flows can affect areas far beyond the initial failure site. This gap highlights the strategic importance of local governance within disaster risk reduction frameworks. Local Self Governments (LSGs) are ideally situated to act as primary responders and spatial planners, possessing the institutional capacity to identify vulnerable populations, enforce land-use zoning, and implement community-based risk mitigation strategies. Their localised expertise, administrative authority, and proximity to affected communities enable them to deliver context-specific, people-centred interventions (FAO, 2007; Bang, 2013; UNDRR, 2010,1; KSDMA, 2020). Strengthening the capabilities of Local Self Governments (LSGs) through technical training, community-based mapping, and the incorporation of spatial planning tools can improve both preparedness and resilience (Bang, 2013; Dixon et al., 2022).

In the present research, the authors propose a comprehensive, LSG-focused approach to landslide susceptibility and risk mitigation in two significant LSGs in the Western Ghats: Vathikudy and Mariyapuram LSGs in Idukki district, as well as the upper catchment area of the Manimala River Basin. These sites have experienced recurrent landslide incidents in recent years, triggered by heavy rainfall and exacerbated by unregulated development (Kuriakose et al., 2009a; Prasannakumar and Vijith, 2012; KSDMA, 2020; Ajin et al., 2022; Amrutha et al., 2023; Pradeep et al., 2023). Vathikudy and Mariyapuram, located in the high-relief regions of the Western Ghats, serve as typical examples of inherent vulnerability, whereas the upper Manimala catchment illustrates downstream susceptibility to sediment movement and debris flows.

This study aims to comprehensively assess landslide susceptibility in these areas, addressing both intrinsic factors

such as slope, geology, soil, and land use, and downstream factors including sediment transport, debris flow, and flood potential. The research seeks to generate high-resolution, LSG-scale landslide susceptibility maps, integrate scientific risk assessments with local governance and planning frameworks, and propose site-specific mitigation strategies to enhance disaster preparedness, community resilience, and sustainable development. By doing so, the study aims to develop a replicable geospatial model that integrates scientific evaluation with decentralised governance for effective landslide risk management.

2 Study area

The areas — Vathikudy, Mariyapuram, and the upper catchment area of the Manimala River — were selected for the present research due to the frequency of landslide incidents in the region and the region's higher vulnerability to slope failures. In recent years, these areas have recorded an increased frequency of landslides, particularly during the monsoon season (SDMA, 2015; Kanungo et al., 2020; Pradeep et al., 2023). A major landslide occurred in October 2021 in Kootickal, in the upper catchment of the Manimala, resulting in extensive damage and loss of life (Ajin et al., 2022; Amrutha et al., 2023). This incident underscored the critical need to evaluate landslide risk in the area. Similarly, the Mariyapuram and Vathikudy areas in the Idukki district have experienced recurrent landslide events, impacting local populations, agriculture, and transportation networks (Kanungo et al., 2020; Pradeep et al., 2023). Steep slopes, weathered rock formations, and heavy rainfall characterise these regions, rendering them ideal for investigating landslide susceptibility and impacts along the downslope movement path using geospatial methodologies.

The first study area comprises the Vathikudy and Mariyapuram LSGs in Idukki district, Kerala. Vathikudy LSG, positioned at 9°54' N, 77°2' E, includes the key towns of Thopramkudy and Murickassery. Mariyapuram, situated at 9°51' N, 77°013' E, lies approximately 5 km east of the district headquarters, Painavu, and near the Idukki–Kanjikuzhy corridor (Fig. 1A). This region is part of the highland zone of Kerala. It is highly susceptible to slope failures due to its steep terrain (slope angles ranging from 0° to 66°), fragile geology, and intensive land-use practices (Kanungo et al., 2020; Pradeep et al., 2023). The second study area is the upper catchment of the Manimala River, which originates in the Mothavara hills of the Western Ghats. The catchment is geographically located between 9°21' to 9°40' N latitude and 76°33' to 76°58' E longitude, spanning across parts of the Idukki and Kottayam districts (Fig. 1B). The Peerumedu plateau, a unique geomorphic surface with extensive plantations, characterizes the eastern segment of the catchment. The plateau edge is dissected by first-, second-, and third-order tributaries of the Manimala River, featuring steep elevation drops of up to 1000 meters between the stream sources and their confluences. It shows youthful upper catchment morphology in this region.

The selected study areas exhibit diverse land cover, including natural forests, rubber and tea plantations, agricultural lands, and open areas. Geologically, the area is

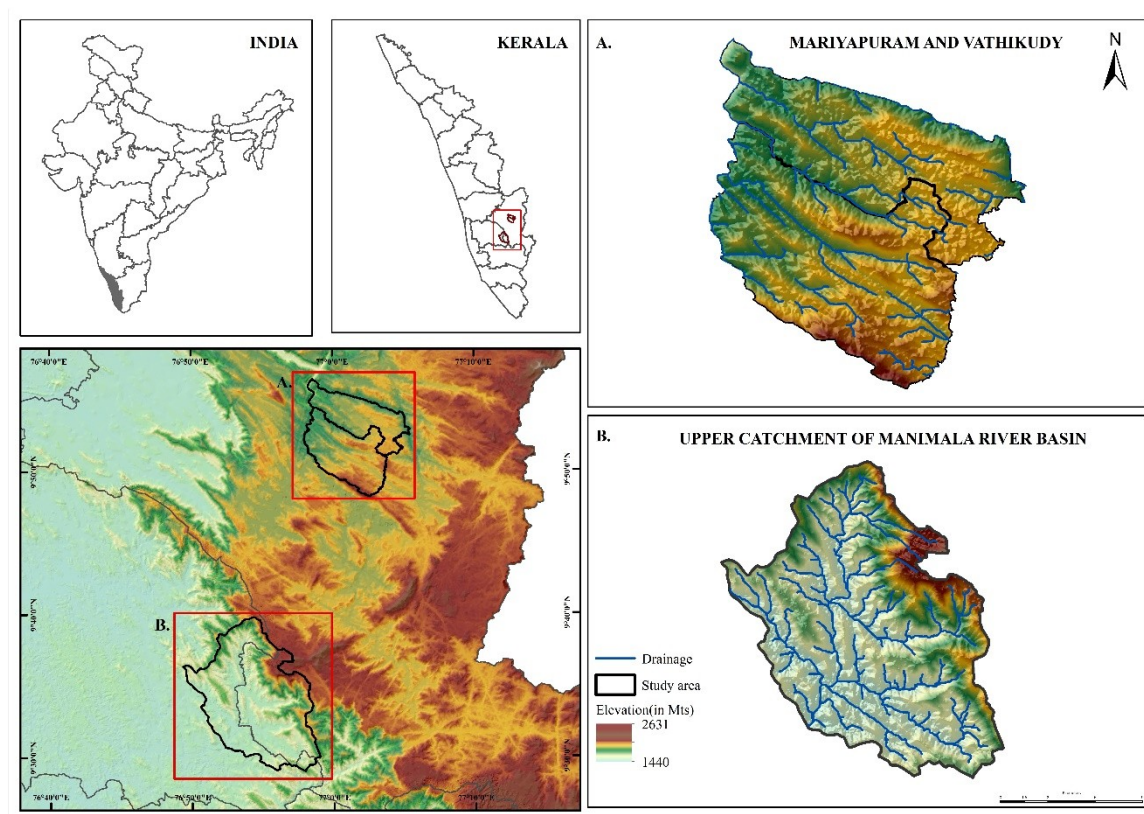


Fig. 1. Location of the Study area A Mariyapuram and Vathikudy B. Upper catchment of Manimala river basin.

composed of hard crystalline rocks, including quartzite, charnockite, biotite gneiss, and dolerite. The vast majority of the area is covered by charnockites, which occupy more than 90% of the total study area (Santosh, 2020; Abraham et al., 2021). Geomorphology of the area heavily depends on regional geological characteristics and rainfall patterns, and major features present in the area include structural hills, slopes, valleys, denudational hills, mounds, etc. (Prasannakumar and Vijith, 2012; Vijith et al., 2014; Sajinkumar and Anbazhagan, 2015). As a monsoon-dominated state, the study area receives an annual average rainfall of more than 3500 mm from two dominant monsoon seasons, such as the south-west and north-east monsoons. The temperature in the study area ranges from 19 °C to 34 °C, with a mean daily temperature of 26 °C. Major land use/land cover present in the study area are forest, plantations, croplands, paddy fields, grasslands and open scrub. These two areas were selected together for this study because they represent contrasting yet complementary geomorphic and land-use settings within the landslide-prone Western Ghats. While both regions experience similar climatic conditions, including intense monsoonal rainfall and fragile geology, they differ in landscape configuration: one is a settlement-dominated highland region (Vathikudy–Mariyapuram), and the other is a fluvially dissected catchment (upper Manimala). Studying these areas together allows for a comparative evaluation of how different combinations of terrain, land use, and drainage characteristics influence landslide susceptibility and downstream impacts. This integrated approach enhances understanding of regional landslide dy-

namics and supports more effective disaster risk management strategies across similar settings in the Western Ghats.

3 Datasets and methods

3.1 Datasets

To produce the Landslide Susceptibility Zonation (LSZ) maps for the study areas, a comprehensive compilation of spatial and non-spatial datasets was assembled from various credible sources. The administrative boundary for Mariyapuram–Vathikudy was obtained from Panchayat-level maps, whereas the boundary of the Manimala Basin was defined using Survey of India toposheets. The landslide inventory data, which served as the basis for the susceptibility analysis, identified 105 palaeoslides initiation sites in Mariyapuram–Vathikudy and 44 in the Manimala Basin, and were sourced from the Geological Survey of India’s Bhukosh Landslide Inventory (<https://bhukosh.gsi.gov.in/Bhukosh/Public>). The research accounted for several conditioning factors known to affect landslide occurrences, including slope, relief, land use/land cover (LULC), drainage density, geomorphology, and proximity to streams and roads. Topographic data were obtained from the SRTM DEM with a 30 m (1 arc-second) spatial resolution, referenced to the WGS 84 datum, and accessed via the USGS Earth Explorer portal. The DEM was mosaicked and clipped to fit the specific extents of the study area and was further processed to derive slope, elevation, and drainage network layers, which were utilized as inputs for terrain analysis. Land use, land cover, and road network layers

were produced through meticulous visual interpretation of high-resolution, multi-temporal satellite imagery sourced from Google Earth Pro. The application of multi-date imagery enabled cross-verification of features, while ground-truth verification improved positional accuracy. Digitization was performed at a uniform viewing scale to ensure accuracy, with mapping decisions influenced by distinct tonal variations, textural patterns, and contextual relationships observable in the imagery. Additionally, geomorphological data were incorporated to capture terrain-form and process characteristics pertinent to slope instability. All spatial datasets were combined in a common coordinate system to maintain analytical consistency. Data preprocessing, integration, and spatial analysis were conducted using ArcGIS 10.8 and QGIS 3.34.7, with Google Earth Pro serving as a key platform for interpretation.

3.2 Methodology

This research employed a systematic approach that integrated spatial data preparation, statistical modelling, and hazard impact assessment to produce reliable maps of landslide susceptibility and downstream impacts. The process included the preprocessing of thematic layers representing critical conditioning factors, the application of the frequency-ratio (FR) model to evaluate their correlation with historical landslide events, the development of a Landslide Susceptibility Index (LSI), and the execution of a downstream impact analysis to pinpoint regions at risk of secondary effects.

3.2.1 Pre-processing

The landslide inventory was randomly divided into two groups—70% allocated for model training and 30% for validation—to reduce selection bias. The training dataset was used to determine the weights for individual variable classes to create the Landslide Susceptibility Zonation (LSZ) map. In contrast, the validation dataset was utilised to evaluate its predictive performance. Relief and slope layers were extracted from the SRTM DEM using the Spatial Analyst extension of ArcGIS 10.8. Drainage networks were defined using the Hydrology extension, and drainage density was computed using the Line Density tool. The same drainage network was used to create the distance-to-streams layer using Euclidean Distance analysis. Distance-to-road layers were generated from road networks digitised in Google Earth Pro. All variables were projected to WGS 1984 UTM Zone 43N before analysis.

3.2.2 Landslide susceptibility analysis

The assessment of landslide susceptibility was conducted using the frequency-ratio (FR) model, a commonly used bivariate statistical technique for measuring the relationship between landslide occurrences and their causative factors (Vijith and Madhu, 2007,0).

For each thematic class, the FR was computed as:

$$FR = \frac{\text{landslide occurrence percentage}}{\text{area occurrence percentage}}$$

The frequency-ratio (FR) values were computed for each

thematic layer, resulting in a table that illustrated the relative impact of each class on landslide occurrences. These ratios were subsequently spatially reclassified in ArcGIS, and the Landslide Susceptibility Index (LSI) was generated by superimposing the weighted thematic layers using the Raster Calculator tool in the Spatial Analyst extension. The resulting LSI raster was then categorised into susceptibility zones that indicate different levels of landslide risk.

3.2.3 Downstream impact assessment

Following the assessment of landslide susceptibility, a downstream risk evaluation was conducted to pinpoint and delineate areas that could be affected by the cascading consequences of upstream landslides, including debris flows, stream obstructions, and sediment accumulation. This stage is crucial for understanding the secondary impacts of landslides on communities downstream, infrastructure, and river systems. High-resolution satellite imagery available in Google Earth Pro was used to manually outline susceptible downstream regions, with particular focus on settlements along both primary and secondary drainage channels. The outlining process involved a visual examination of terrain features, flow patterns, and the proximity of downstream elements to the identified landslide-prone slopes. By overlaying the landslide susceptibility map with layers from Google Earth depicting settlements, roadways, and river systems, the downstream impact zones were classified based on their vulnerability to potential debris flow paths from landslides. The downstream impact areas identified through this methodology are vital components for local disaster risk reduction strategies. They can guide the prioritisation of mitigation efforts and early warning systems within the areas under study.

4 Results and discussion

The susceptibility to landslides in the Mariyapuram and Vathikudy Local Self Governments (LSGs), as well as the upper catchment area of the Manimala River basin, situated on the windward slopes of the Western Ghats, was assessed through frequency-ratio (FR) analysis. The findings offer valuable insights into the spatial variability of landslide-prone areas and the predominant geo-environmental controls throughout the study region (Fig. 2 and Fig. 3).

4.1 Factor Response to Landslide Susceptibility

4.1.1 Slope

The slope of the terrain, which significantly affects the downward movement of water and soil, is a crucial factor in assessing the terrain's vulnerability to slope failure (Montgomery and Dietrich, 1994; Reichenbach et al., 2018)—in Mariyapuram and Vathikudy LSGs, slopes ranging from 15° to 45° exhibit the highest susceptibility to landslides, accounting for 85% of total landslides (Fig. 2A, Table 1). This trend is also evident in the upper catchment of the Manimala River basin, where 76% of landslides are recorded (Fig. 3A, Table 2). This specific slope range marks a critical threshold where the gradient is sufficiently steep to generate substantial shear stress, while still retaining sufficient soil

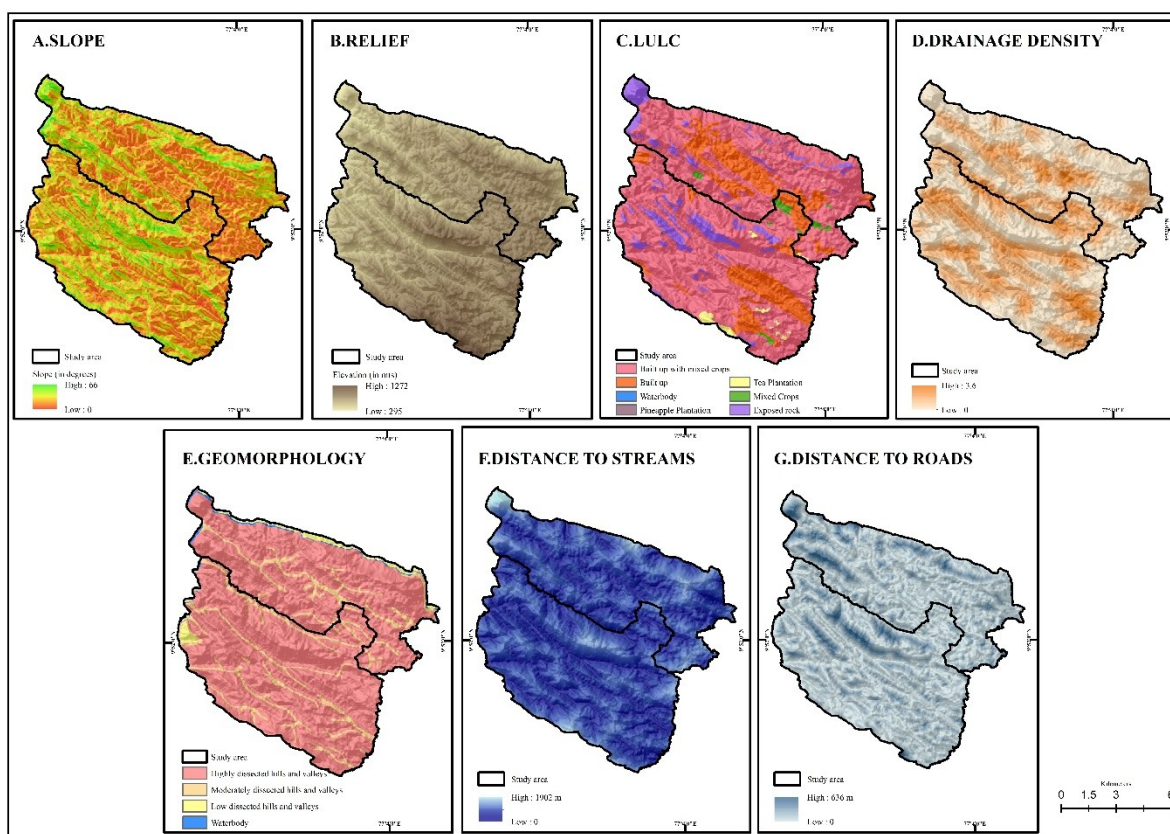


Fig. 2. Variables considered for the landslide susceptibility of Mariyapuram and Vathikudy. A. Slope, B. Relief, C. LULC, D. Drainage density, E. Geomorphology, F. Distance to stream, G. Distance to roads.

and weathered material to promote failure. Most landslides in the Western Ghats occur on slopes exceeding 20° (Kuriakose et al., 2009a; Prasannakumar and Vijith, 2012), with increased vulnerability noted between 30° and 45° .

4.1.2 Relief

Relief plays a crucial role in determining landslide susceptibility on the windward slopes of the Western Ghats (Reichenbach et al., 2018; Emberson et al., 2022). Frequency-ratio analysis conducted at both locations reveals that the 250–500 m elevation range exhibits the highest susceptibility, with significant landslide occurrences extending up to 750 m. In the Mariyapuram Vathikudy area, approximately 47% of landslides occur within the 500–750 m range (Fig. 2B, Table 1). Similarly, in the upper catchment of Manimala, around 60% of landslides are recorded in this elevation zone (Fig. 3B, Table 2). These mid-elevation areas are characterized by steep slopes, active land use, and high exposure to rainfall, all of which contribute to increased slope instability. Furthermore, the weathered bedrock and colluvial materials found at these altitudes are particularly vulnerable to saturation and failure during periods of heavy rainfall.

4.1.3 LULC

Land Use and Land Cover (LULC) encompasses both natural processes and human activities that affect slope

stability, either directly through physical changes or indirectly through ecological consequences (Reichenbach et al., 2018). In the Mariyapuram Vathikudy area, built-up areas with mixed crops are the most susceptible to landslides. This is mainly attributed to slope alterations resulting from unplanned construction, the removal of deep-rooted vegetation, and inadequate drainage systems. These elements contribute to increased surface runoff, diminished soil cohesion, and heightened pore-water pressure during rainfall, thereby triggering slope failures. The cumulative impact of human pressure and disrupted land cover significantly undermines slope stability in these areas (Vijith and Madhu, 2008; Anbalagan et al., 2015) (Fig. 2C, Table 1).

In the upper catchment area of the Manimala River basin, there is a high incidence of landslides in rubber plantation areas. In contrast to natural forests, rubber plantations exhibit shallow root systems, limited undergrowth, and modified canopy structures, which diminish slope reinforcement and soil moisture retention. These factors contribute to increased surface runoff and soil saturation during heavy rainfall, thereby exacerbating slope instability. Furthermore, plantation management practices such as terracing, land clearing, and the establishment of unpaved access roads further disrupt the terrain. Monoculture plantations, especially rubber, are significant contributors to the heightened susceptibility to landslides in the Western Ghats (Ajin et al., 2022) (Fig. 3C, Table 2).

Table 1. Frequency ratio of Mariyapuram Vathikudy area.

Layer	Class	Landslide%	Area%	Fr
Slope	0–15	0.13	0.44	0.30
	15–30	0.72	0.41	1.74
	30–45	0.14	0.08	1.85
	45–60	0	0	0
	60–65.869	0	0	0
Relief	295–500	0.07	0.02	3.39
	500–750	0.48	0.40	1.19
	750–1000	0.45	0.49	0.92
	1000–1272	0.01	0.04	0.22
LULC	Built up with mixed crops	0.94	0.73	1.23
	Built-up area	0.03	0.17	0.17
	Tea plantation	0	0.01	0
	Mixed crops	0	0.01	0
	Rock exposure	0.03	0.08	0.36
	Water body	0	0	0
	Pineapple plantation	0	0	0
Drainage density	0–1	0.53	0.56	0.91
	1–2	0.39	0.32	1.20
	2–3	0.08	0.09	0.92
	3–3.62	0	0	0
Geomorphology	Highly dissected area	0.89	0.86	1.04
	Moderately dissected area	0.07	0.11	0.60
	Low dissected area	0.02	0.02	0.83
	River	0.02	0.01	2.14
Distance to stream	0–400	0.73	0.66	1.12
	400–800	0.24	0.31	0.77
	800–1200	0	0.03	0
	1200–1600	0.03	0.01	6.36
	1600–1901.63	0	0	0
Distance to road	0–150	0.89	0.79	1.13
	150–300	0.09	0.17	0.56
	300–450	0.01	0.04	0.24
	450–600	0	0	0
	600–635.68	0	0	0

4.1.4 Drainage density

Watercourses sculpt the Earth's surface and can compromise slope integrity by eroding their bases and facilitating water infiltration, which increases the likelihood of slope failure (Gorum et al., 2011; Shankar et al., 2022). A moderate drainage density (1–3 km/km²) typically indicates regions where slopes are frequently intersected by streams, leading to active toe erosion and destabilisation of slope foundations. These regions also promote greater water infiltration during heavy rainfall events, raising pore-water pressure and diminishing the soil's shear strength, ultimately leading to slope failures. This relationship is particularly critical in the Western Ghats, where intense monsoonal rainfall serves as a primary triggering factor (Fig. 2D, Fig. 3D, Table 1, Table 2).

4.1.5 Geomorphology

Landforms, or geomorphology, illustrate the configuration and characteristics of the Earth's surface, shaped by prolonged natural processes (Yunus et al., 2021; Shankar et al., 2022; Amrutha et al., 2023). Prominent river corridors and extensively dissected terrains exhibit a high frequency of landslides. Riverbanks are susceptible to toe erosion and saturation during intense rainfall, which diminishes slope stability. Areas with significant dissection display steep inclines, intricate drainage systems, and considerable relief, all of which amplify surface runoff and gravitational stress. Collectively, these elements increase the likelihood of landslides (Fig. 2E, Fig. 3E, Table 1, Table 2).

4.1.6 Distance to streams

Landslides at both locations predominantly occur at considerable distances from first-order streams. In the Mariyapuram–Vathikudy LSGs, landslides are mainly

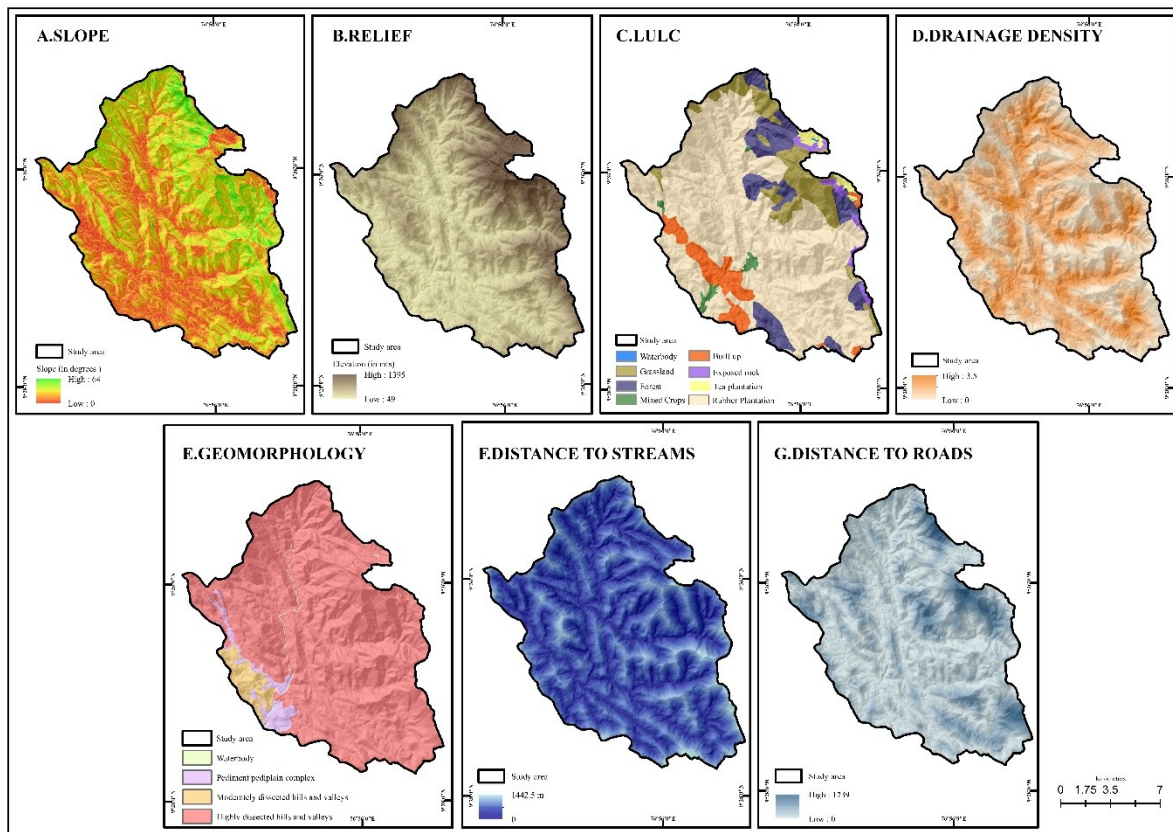


Fig. 3. Variables considered for the landslide susceptibility of the upper catchment of the Manimala basin. A. Slope, B. Relief, C. LULC, D. Drainage density, E. Geomorphology, F. Distance to stream, G. Distance to roads.

observed within 1200–1600 m from first-order streams, whereas in the upper Manimala region, they occur within 900–1442 m. These areas frequently lack effective surface drainage, leading to greater water retention and increased pore pressure during heavy rainfall and compromising slope stability. In the Western Ghats, internal groundwater movement and lateral seepage are critical triggers of landslides (Kuriakose et al., 2009a; Das et al., 2023). Additionally, in certain regions of the Western Ghats, elevated landslide frequencies are noted at moderate distances from streams due to subsurface saturation and human activities (Achu et al., 2024) (Fig. 2F, Fig. 3F, Table 1, Table 2).

4.1.7 Distance to roads

The development of road networks in mountainous areas is a significant anthropogenic factor that heightens the vulnerability of slopes to erosion and downslope movements. Unplanned, scientifically unsound road construction in hilly regions destabilises slopes by removing essential toe support, thereby increasing the likelihood of slope failures and posing serious risks to human life and infrastructure (Das et al., 2023).

Landslides on the windward slopes of the Western Ghats are significantly associated with proximity to roads, with the majority occurring within 150 meters and all within 450 meters. This trend is largely attributed to the destabilisation of slopes resulting from road construction activities, including cut-and-fill operations, slope undercutting, insuffi-

cient drainage, and vegetation removal. Such modifications enhance water infiltration and increase pore pressure, particularly during heavy monsoon rainfall, which contributes to slope failure. In the Darjeeling Himalayas, 70% of landslides occurred within 100 meters of roads (Sarkar and Kunnungo, 2004; Dikshit et al., 2018). The relationship between landslide occurrences and proximity to roads is particularly pronounced in mountainous areas such as the windward slopes of the Western Ghats. Road construction typically entails significant alterations to slopes, including excavation, cut-and-fill operations, and vegetation removal, all of which compromise the stability of natural slopes. These disruptions alter the hydrological system by blocking or redirecting natural drainage, leading to increased water infiltration and pore pressure—critical factors in slope failure, especially during severe monsoon rains. Furthermore, the absence of adequate slope protection and drainage systems further intensifies the instability (Figs. 2G, 3G, Tables 1, 2).

4.2 Landslide Susceptibility

The landslide susceptibility map for the Mariyapuram Vathikudy region, created using frequency-ratio analysis, categorizes the 112.26 km² study area into three zones: high (17.52%), moderate (65.78%), and low (16.69%) susceptibility. The significant presence of the moderate zone suggests a broad landscape characterized by moderately steep slopes, diverse land use, and intermediate drainage features, which

Table 2. Frequency ratio of upper catchment of Manimala.

Layer	Class	Landslide%	Area%	Fr
Slope	0–15	0.24	0.40	0.60
	15–30	0.65	0.42	1.55
	30–45	0.11	0.13	0.85
	45–60	0	0	0
	>60	0	0	0
Relief	49–250	0.35	0.46	0.75
	250–500	0.52	0.27	1.91
	500–750	0.09	0.09	0.91
	750–1000	0.04	0.06	0.66
	>1000	0	0.05	0
LULC	Rubber plantation	0.76	0.68	1.11
	Tea plantation	0	0.01	0
	Reservoir	0		0
	Grassland	0	0.02	0
	Rock exposed	0.11	0.11	1.01
	Built-up	0.04	0.06	0.70
	Forest	0.09	0.11	0.82
	Mixed crops	0	0.01	0
Drainage density	0–1	0.46	0.53	0.86
	1–2	0.43	0.38	1.14
	2–3	0.09	0.08	1.02
	>3	0.02	0.01	9.36
Geomorphology	Water body	0.04	0	11.80
	Pediment Padi plain complex	0	0.03	0
	Moderately dissected hills and valleys	0	0.04	0
	Highly dissected hills and valleys	0.96	0.92	1.04
Distance to stream	0–100	0.26	0.20	1.33
	100–300	0.28	0.33	0.86
	300–600	0.41	0.34	1.22
	600–900	0.02	0.12	0.18
	900–1442	0.02	0.01	1.51
Distance to road	0–50	0.72	0.19	3.68
	50–350	0.22	0.51	0.42
	350–700	0.06	0.19	0.34
	700–1100	0	0.08	0
	1100–1739	0	0.02	0

indicate conditional instability. High susceptibility zones are linked to steep slopes, elevated stream density, proximity to roadways, and human-induced disturbances, all of which considerably compromise slope stability during heavy rainfall. Conversely, low susceptibility regions are defined by gentle slopes, abundant vegetation, and limited human influence (Fig. 4A, Table 3)

The landslide susceptibility map for the upper catchment area of the Manimala River Basin, which encompasses 189.6813 km², has been divided into three susceptibility zones: high, moderate, and low. These indicate that the high-susceptibility zone covers 25.37%, the moderate-susceptibility zone extends over 70.45%, and the low-susceptibility zone covers 4.18% of the overall area. The prevalence of the moderate zone reflects a broad terrain with transitional slope conditions and land use prac-

tices that contribute to its conditional instability, while the high susceptibility zones are typically associated with steep slopes, high stream density, and human-induced disturbances (Fig. 4B, Table 3).

4.3 Downstream Impact Analysis

Debris flows are prevalent in India's mountainous regions, especially in the Himalayas and the Western Ghats, typically instigated by intense monsoon rainfall or cloudburst occurrences (Prasannakumar and Vijith, 2012; Shekhar et al., 2015; Ajin et al., 2022). In the Western Ghats, debris flows are frequently directed along steep stream channels, while in the Himalayas, they are more often initiated by rock falls that develop into debris flows (Prasannakumar and Vijith, 2012; Dash et al., 2022). A recent significant instance is the debris flow in Wayanad

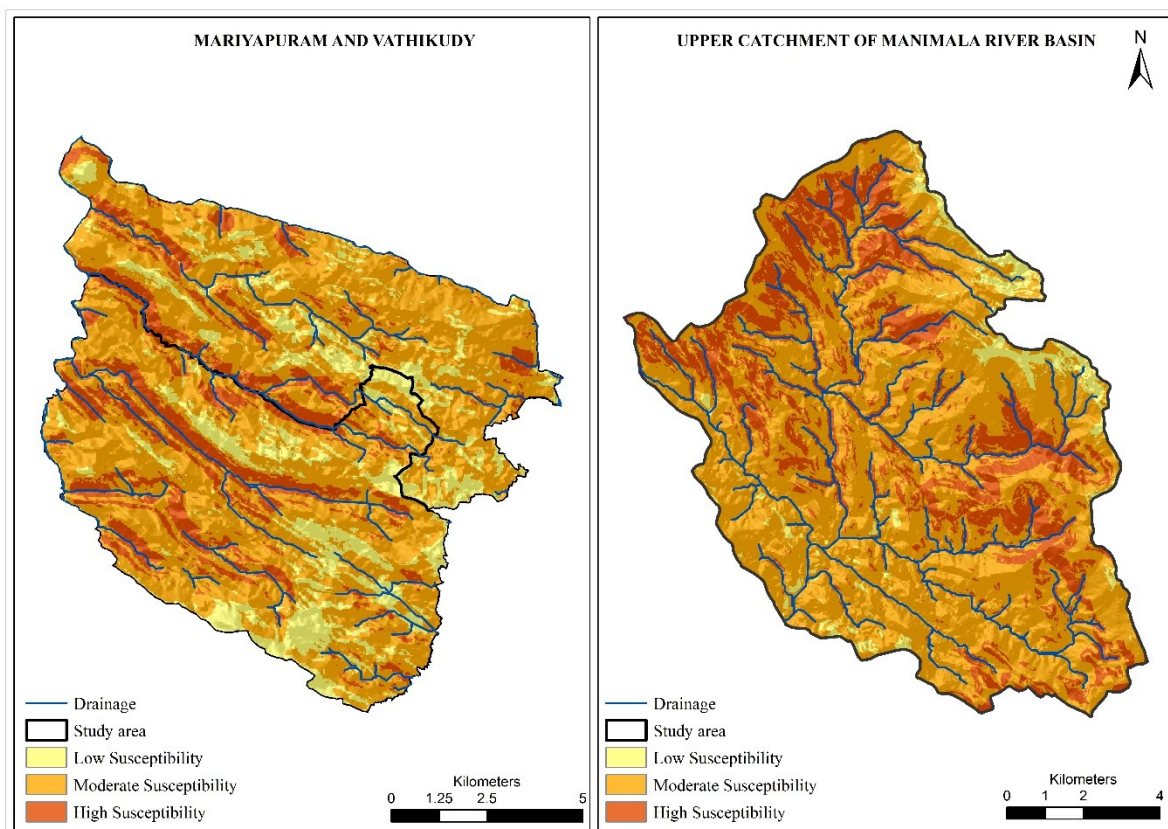


Fig. 4. Landslide susceptibility of A. Mariyapuram and Vathikudy B. Upper catchment of Manimala basin.

Table 3. Landslide susceptible area.

	Landslide susceptible area (km ²)		
	High Susceptibility	Moderate Susceptibility	Low Susceptibility
Mariyapuram and Vathikudy	19.67	73.84	18.74
Upper catchment of the Manimala basin	48.12	133.64	7.93

in July 2024, which is estimated to have mobilized material of quantity between 5.1 and 5.7 million cubic meters (MCM) of material, rendering it one of the largest debris flow incidents in recent Indian history (Krishnapriya et al., 2024; Yunus et al., 2025; Kolathayar et al., 2025). The most extensive damage during this event occurred in the downstream regions of Vellarimala, particularly in Mundakkai and Chooralmala, where numerous residences and public structures were built on river terraces (Soman, 2024). These downstream areas are particularly vulnerable to the cascading effects of landslides, as they often lie along former or active river flow paths and debris channels. When landslide debris is mobilized from higher elevations, it can swiftly move downslope, heightening the risk of river blockages, flash floods, and infrastructure damage. Landslides frequently release substantial amounts of debris, which can obstruct river channels, creating temporary dams that may suddenly fail and provoke catastrophic flooding downstream (Fan et al., 2020). These consequences underscore the need for comprehensive landslide risk assessments that account for both upstream hazards and downstream vulnerabilities.

The downstream impact analysis in the study area was performed by integrating the landslide susceptibility map

with hydrological flow paths and settlement locations using Google Earth Pro. The delineated flow paths within the basin suggest that debris from high-susceptibility areas is likely to be carried along the primary channels. The downstream movement of landslide debris poses a cascading risk that can affect regions far from the original landslide location (Luo et al., 2022). These flow paths illustrate the likely routes of debris transport linking the sites of landslide initiation to downstream regions.

Several transient sediment convergence points were recognized along the flow paths, typically occurring at stream confluences and terrain flattening points. These transient sediment convergence points are vital because they can temporarily hold debris, thereby increasing the risk of stream blockages and the formation of debris dams. The potential collapse of such dams poses a significant secondary risk, including the possibility of sudden downstream flooding. Settlements located along primary flow paths, especially near flow accumulation points, have a significant downstream impact. These communities are particularly susceptible to direct effects from debris flow, flash flooding, and sediment deposition. The proximity of human settlements to the identified high-risk streams underscores the need for ongoing

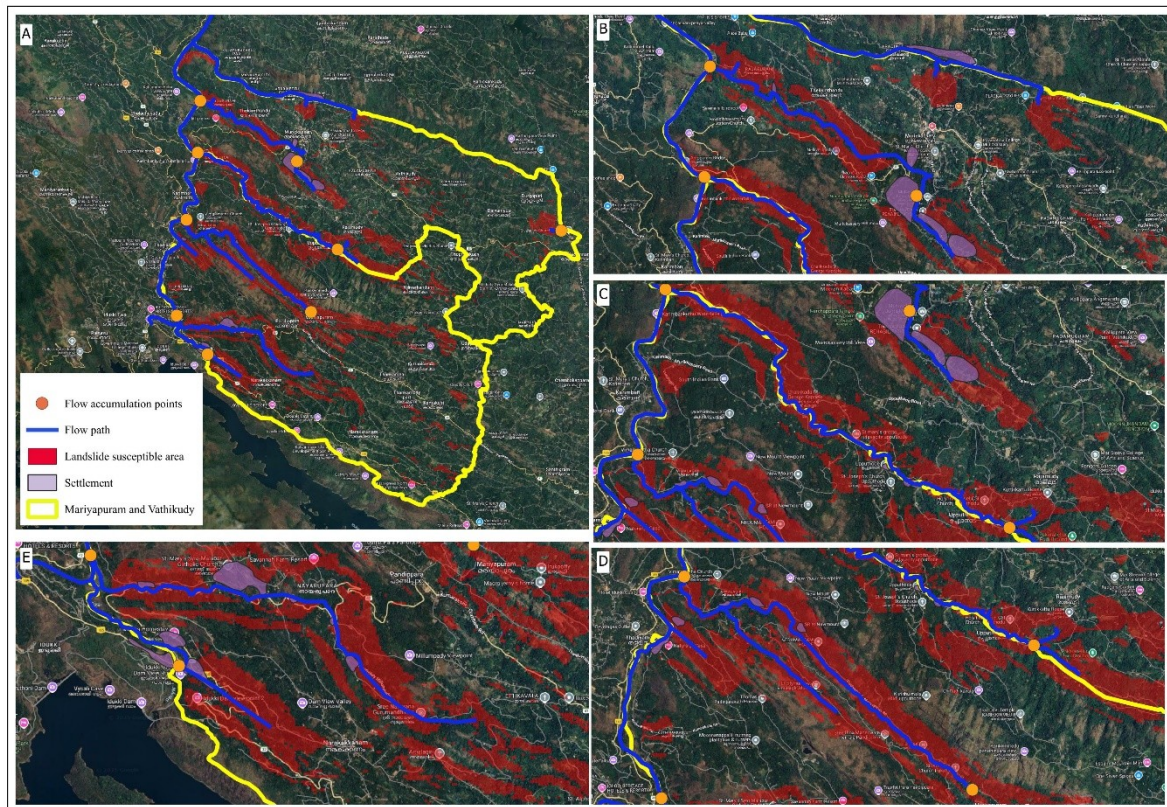


Fig. 5. A. Landslide susceptibility and flow path of Mariyapuram-Vathikudy LSG, B. Transient sediment along convergence point Valiyaveetil Padi thodu, C. Vimalagiri Karikkil thodu and Upputhodu, D. Transient sediment convergence point along Cheruthonipadi thodu, E. Transient sediment convergence point along Periyar thodu.

ing monitoring and the implementation of community-based early warning systems.

The assessment of landslide susceptibility and downstream impact for the Mariyapuram and Vathikudy Local Self Government (LSG) regions has shown that the landscape is marked by alternating uplands and valleys arranged in a grooved configuration. These valleys, generally located between two extended hill ridges, function as natural conduits for surface runoff and displaced debris resulting from slope failures. The geomorphological features strongly indicate that these valleys serve as primary channels directing flow towards the main Periyar River system and function as potential zones for flow accumulation (Fig. 5A). Comprehensive spatial analysis reveals that flow convergence is probable along the Valiyaveetil Padi Thodu (Fig. 5B), Vimalagiri Karikkil Thodu, Upputhodu (Fig. 5C), Cheruthonipadi Thodu (Fig. 5D) and Periyar Thodu (Fig. 5E). These waterways are anticipated to promote the swift downstream transport of landslide debris and surface runoff, particularly during periods of intense rainfall. In light of the flow accumulation trends and the orientation of vulnerable slopes, several downstream communities, including Kuthirakkallu, Vimalagiri, Upputhode, Antopuram, and Rajapuram, have been identified as significantly at risk of secondary hazards such as debris flow inundation and flash flooding. The concentration of flow in these regions heightens the likelihood of material accumulation and the potential obstruction of channels, which can

worsen localized flooding and inflict damage on infrastructure and agricultural lands. The Mariyapuram–Vathikudy LSG region is situated within a moderately dissected hilly landscape, where zones prone to landslides are scattered across various tributaries. This area displays extensive flow paths and numerous points of flow accumulation, suggesting a diffused convergence of debris rather than a movement concentrated in channels. Such geomorphological characteristics amplify the risk of extensive downstream effects, particularly where human settlements intersect with these flow paths. The terrain facilitates lateral debris dispersal before it reaches the main valleys, thereby complicating hazard zoning.

The high elevated regions within the upper catchment area of the Manimala River basin are recognized as the most vulnerable to landslides. The areas prone to landslides are primarily situated along the slopes of escarpments and steep valleys, where geological formations influence the movement of water and debris. This distribution corresponds with established findings that topographic elevation and slope angle are key factors in the initiation of landslides (Guzzetti et al., 1999). The hydrological connectivity within the basin significantly impacts the downstream movement of debris. Transient sediment convergence points have been identified at critical junctures where smaller streams merge with larger, higher-order streams, thereby increasing the likelihood of debris accumulation and downstream transport (Fig. 6A). A notable transient sediment convergence point

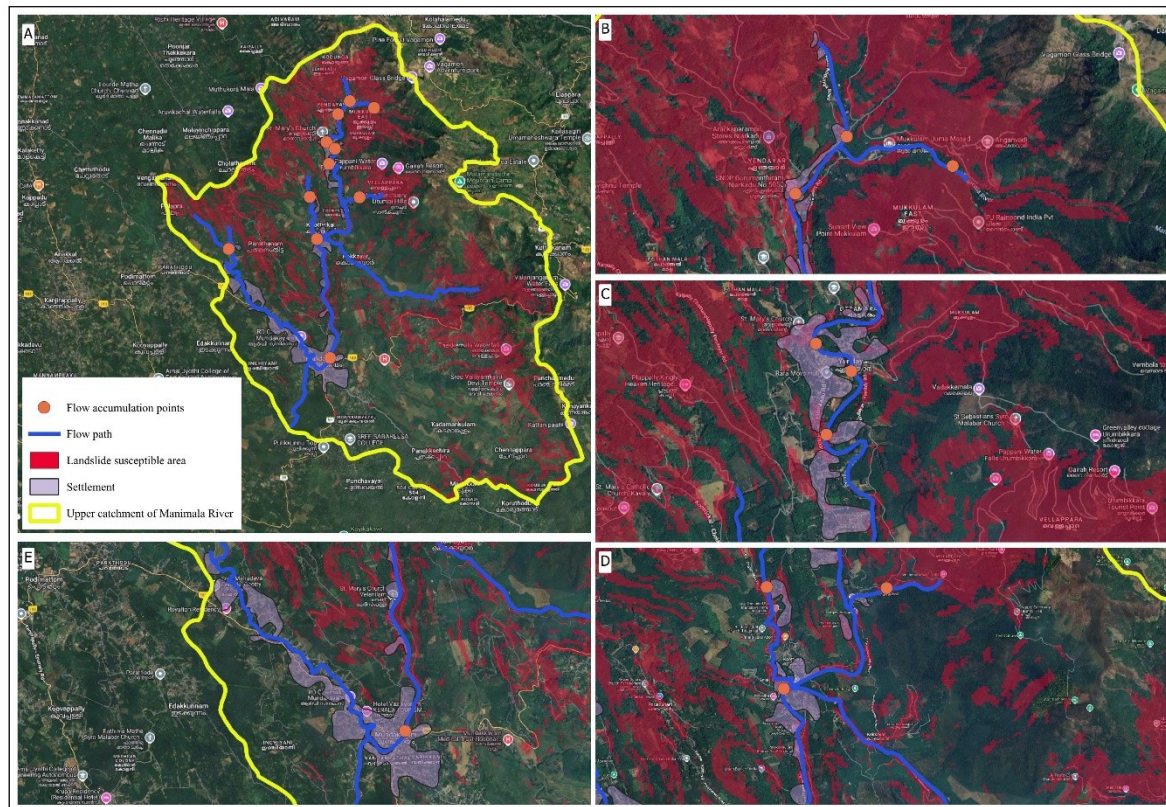


Fig. 6. A. Landslide susceptibility and flow path of upper catchment of Manimala river basin, B. Transient sediment convergence point at the junction of Kodunga Thodu and Pullakayar, C,D. Transient sediment convergence point along Pullakayar, E. Transient sediment convergence point at Ettilathodu source area.

occurs at the junction of Kodunga Thodu and a 4th order stream, which forms the Pullakayar. This confluence acts as a crucial node for the collection of debris and water, heightening the risk of downstream debris flows during periods of intense rainfall (Fig. 6B). Such confluence zones have been acknowledged as vital hotspots for sediment transport. Additional flow accumulation points are observed along the Pullakayar, especially where 3rd order streams converge with the main channel (Fig. 6C,D). These confluences enhance the stream's ability to transport debris and sediment downstream, thereby increasing the risk to communities situated along the riverbanks. The source area of Ettiolithodu also serves as a flow-accumulation zone (Fig. 6E). Although often neglected, headwater accumulation zones can initiate localised debris flows that may merge into larger downstream events.

The downstream impact assessment reveals that several significant settlements are directly vulnerable to the possible effects of debris flows and flash flooding: Konnadu Town, Yendayar, Mundakkayam, and Velanilam. These towns are situated near major flow paths and recognized flow accumulation points, which considerably heightens their susceptibility to cascading hazards. Settlements such as Yendayar and Mundakkayam are located along primary river courses downstream of various debris transport routes. This geographic location increases the likelihood of being affected by both direct debris flows and the potential failure of debris dams, which could result in abrupt flooding.

Communities located near transient sediment convergence zones and the confluences of major streams face a disproportionately elevated risk during debris flows. The presence of these settlements along precarious flow corridors necessitates immediate risk mitigation measures, including slope stabilisation in upstream catchments, construction of debris-retention structures, and implementation of real-time monitoring systems. In fluvially dissected catchments such as the upper Manimala basin, steep slopes and intricate stream networks enhance sediment connectivity. Landslide debris is swiftly transported downslope through channels, resulting in severe downstream consequences, particularly where settlements are established on river terraces or valley floors.

4.4 Disaster Risk Reduction (DRR) Implications

The analysis of landslide susceptibility in the downstream areas of the Mariyapuram–Vathikudy LSG and upper Manimala Basin underscores significant zones of flow accumulation, points of transient sediment convergence, and at-risk settlements. These insights are instrumental in formulating disaster risk reduction (DRR) strategies tailored to mitigate the threats posed by debris flows, obstructed waterways, and abrupt flooding. In Mariyapuram–Vathikudy, the existence of numerous tributaries and expansive valleys facilitates the lateral dispersion of debris, thereby heightening the vulnerability of settlements such as Kuthi-

rakkallu, Vimalagiri, Upputhode, Antopuram, and Rajapuram. The disaster risk reduction (DRR) strategy for this area should prioritize decentralized, small-scale measures, including check dams, silt traps, and enhanced stormwater drainage systems to effectively manage localized debris flows. The importance of hazard zoning cannot be overstated, given the dispersed flow paths, and the delineation of buffer zones along significant channels such as Periyar Thodu and Vimalagiri Karikkil Thodu can aid in regulating future development. Community-level DRR initiatives, which encompass the establishment of local disaster monitoring committees, participatory risk mapping, and awareness programs in schools, will bolster preparedness in the face of landslides triggered by monsoon conditions.

The geomorphological assessment indicates that communities such as Konnadu, Yendayar, Mundakkayam, and Velanilam, situated near key debris transport routes like the Kodunga Thodu–Pullakayar confluence, are at heightened risk downstream. It is advisable to implement structural DRR interventions, including debris retention basins, check dams, and bioengineered reinforcements along riverbanks, for areas identified as high-risk flow paths. Furthermore, techniques for slope stabilization, such as vegetative cover and retaining walls, along with early warning systems based on rainfall thresholds, can significantly diminish the chances of sudden debris flow incidents. Non-structural strategies, including the development of hazard zonation maps, establishment of construction buffer zones, and regulated land use planning on river terraces, should be incorporated into the planning processes of Local Self Governments (LSG). Additionally, community-oriented initiatives, such as evacuation drills, awareness campaigns, and the training of local monitoring teams, are vital for enhancing resilience.

The results of this research are consistent with the objectives outlined in the Sendai Framework for Disaster Risk Reduction (2015–2030), particularly emphasizing the necessity to ‘understand disaster risk’ (Priority 1) and to ‘invest in disaster risk reduction for resilience’ (Priority 3). By integrating landslide susceptibility assessments with structural interventions, real-time monitoring, and risk-sensitive land use planning at the policy level, these DRR strategies can substantially mitigate future disaster-related losses. The incorporation of these recommendations into District Disaster Management Plans (DDMPs) and the guidelines of the Kerala State Disaster Management Authority (KSDMA) will ensure that local governance takes a proactive stance in addressing hazards both upstream and downstream.

5 Conclusions

The present study demonstrates the critical importance of understanding landslide susceptibility and downstream impacts to guide disaster risk reduction in the Mariyapuram–Vathikudy LSGs and the upper Manimala River Basin. The study area exhibits a complex nature of landslide susceptibility, encompassing intrinsic vulnerability driven by steep slopes, hydrological controls, and geomorphological characteristics, conditional instability influenced by human-induced disturbances and land use

practices, and significant downstream susceptibility along drainage networks. Frequency-ratio analysis revealed that moderate to high susceptibility zones dominate the landscape, highlighting areas prone to debris mobilization during heavy rainfall events. These areas, coupled with the geomorphological configuration of grooved valleys and tributary networks, facilitate the rapid transport of landslide debris to downstream settlements, including Kuthirakkallu, Vimalagiri, Upputhode, Antopuram, Rajapuram, Konnadu, Yendayar, Mundakkayam, and Velanilam. Consequently, the cascading effects of debris flows, flash floods, sediment accumulation, and temporary river blockages pose significant threats to human settlements, infrastructure, and agricultural lands.

The study emphasizes that effective disaster risk reduction requires a combination of structural measures (slope stabilization, debris retention basins, riverbank reinforcement) and non-structural strategies (hazard zoning, buffer zones, early warning systems, and community awareness programs). Integrating scientific susceptibility assessments with Local Self Government planning ensures proactive, evidence-based interventions, enhancing resilience and sustainable development in landslide-prone areas of the Western Ghats.

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The authors declare that they have no known conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the datasets used in this research is collected from open source

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